

POLARIZATION EFFECTS IN HADRON STRUCTURE FUNCTIONS AND IN QUARK AND GLUON FRAGMENTATION†

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ABSTRACT

The predictions of QCD for the evolution of the quark and gluon structure functions of a polarized proton are discussed. In fact, the parton polarizations increase with energy, for fixed Feynman x . Thus, polarized protons may be useful for the discovery or investigation of new physical phenomena at very high energy, especially if there are new interactions or particles whose behavior violates one of the natural symmetries of QCD, such as parity. The mean gluon asymmetry grows as $\ln Q^2$, which implies that the orbital angular momentum of the gluons grows similarly.

The evolution of the fragmentation of a parton into a hadron is also governed by QCD. For these, we conjecture that the fragmentation of a quark or gluon into a spinning hadron may well show helicity correlations. The evolution equations then predict an energy evolution similar to the behavior of the structure functions. The spin correlations in fragmentation could be useful in e^-e^+ and $e^\pm p$ reactions with polarized electrons and in deeply inelastic neutrino scattering, even if the hadronic targets are unpolarized.

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Although the spin structure of the proton has received a great deal of attention, especially in the context of the non-relativistic quark model and SU_6 symmetry, the structure functions for very high energy polarized protons has not been exhaustively treated¹. In particular, the implications of perturbative QCD for the energy-evolution of the quark and gluon densities have received relatively little attention until recently². While spin is a fundamental degree of freedom, there is a widespread feeling that polarized hadrons are not very useful because their helicity is shared among their constituents (quarks and gluons). There is a common belief that while the multiplicity of quarks and gluons grows to infinity with increasing energy, their "total net helicity is finite."⁴ Thus the polarization of quarks and gluons is expected to diminish with increasing energy.

In fact, recent work⁵ has shown this prejudice to be, at best, a misleading oversimplification and, at worst, wrong. Although the average parton multiplicity increases with energy, its growth stems from the region of tiny x . Investigation and searches for new physical phenomena frequently involve mass thresholds which place a lower limit on the value of x which a parton may have in order to participate in the process of interest. As a result, these processes are relatively insensitive to the increasing multiplicity of partons.

Moreover, there is no limit on the net helicity carried by partons. Conservation of angular momentum for a proton of definite helicity may be expressed as

$$\frac{1}{2} = \frac{1}{2} \langle \Delta q \rangle + \langle \Delta G \rangle + \langle L_z \rangle, \quad (1)$$

where $\Delta q = q_+ - q_-$ and $\Delta G = G_+ - G_-$ are the quark and gluon asymmetries, respectively. It is true that the mean quark asymmetry $\langle \Delta q \rangle$ is energy independent, but the mean gluon asymmetry $\langle \Delta G \rangle$ grows as $\ln Q^2$, its growth being compensated by the growth of orbital angular momentum $\langle L_z \rangle$ of the gluons. Even the constancy of $\langle \Delta q \rangle$ is somewhat misleading. One can show that the moments $\Delta q_n \equiv \int dx x^{n-1} \Delta q$ actually increase for $1 < n < \nu$, where ν is a number between 1 and 2. (In practice, $\nu \approx 1.5-1.6$ for the relevant number of quark flavors.) It simply happens that $\Delta q_1 = \langle \Delta q \rangle$ decouples from this growth. In fact, Δq_n resumes growing for $n < 1$.

The constancy of $\langle \Delta q \rangle$ is a consequence of helicity conservation in gluon bremsstrahlung and the vector nature of the gluon coupling to quarks. Helicity conservation actually produces an increase in the valence quark polarization, as expressed by the following theorem: Suppose the valence quark polarization $\Delta V/V$ is monotonically increasing with x at a fixed Q^2 . In fact, we conjecture that

$$Q^2 \rightarrow \infty \quad \frac{\Delta V(x, Q^2)}{V(x, Q^2)} = \lim_{x \rightarrow 1} \frac{\Delta V(x, Q_0^2)}{V(x, Q_0^2)}.$$

Although the behavior of the singlet quark and gluon

distributions is more complicated, numerical solutions of a particular model³ lend quantitative support to the notion that gluon and quark polarizations rise with energy. In Fig.1, we show the anticipated increase in the valence quark polarization $\Delta V/V$ from its input value at $Q^2 = 5(\text{GeV}/c)^2$ to $Q^2 = 5 \cdot 10^4 (\text{GeV}/c)^2$, characteristic of the largest momentum transfers anticipated for HERA.

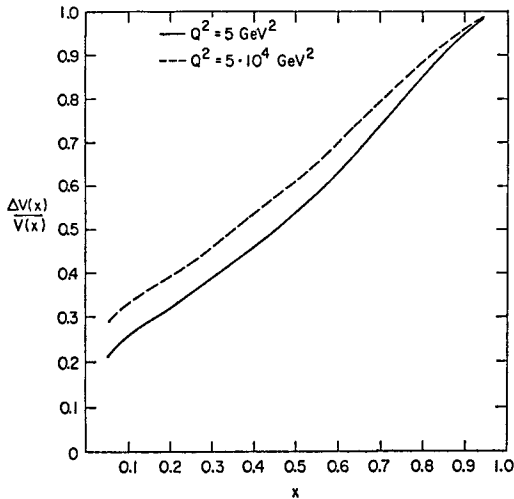


Fig.1 Valence quark polarization $\Delta V(x)/V(x)$ as a function of x for $Q^2=5\text{GeV}^2$ (solid curve) and $Q^2=5 \cdot 10^4 \text{GeV}^2$ (dashed curve) from ref.[9].

(The numerical solution has taken account of only 3 quark flavors and requires the inclusion of more massive quarks before the numerical results can be trusted.) In his contribution to this workshop, J. Soffer has displayed the dramatic rise in gluon polarization $\Delta G/G$.

It would be extremely useful to obtain direct information on the gluon asymmetry. Experiments on prompt photon production already yield some information on the unpolarized gluon structure

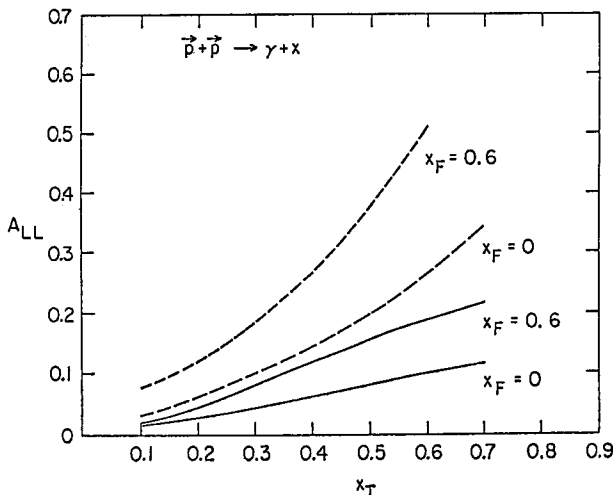


Fig.2 Predictions based on ref.[9] for the double helicity asymmetry A_{LL} in $\vec{p}\vec{p} \rightarrow \gamma X$ at $\sqrt{s}=40\text{TeV}$ for fixed x_F as a function of x_T with $Q^2=5\text{GeV}^2$ (solid curves) and with the evolution scale $Q^2=p_T^2/4$ (dashed curves).

function, and the next generation of such experiments promise to improve our knowledge⁶. Measurements of prompt photon production with a polarized beam and target, $\vec{p}\vec{p} \rightarrow \gamma X$, could provide information on $\Delta G/G$. In Fig.2, we display the double spin asymmetry anticipated for SSC energies, based on the model of ref.3.

The rates are not very encouraging, but given our lack of knowledge of ΔG , the magnitude of this asymmetry is quite uncertain. The rise with energy is a direct consequence of the increasing gluon polarization, which is a consequence of QCD and not expected to be so model-dependent. Experiments of this sort at lower energy are worth entertaining.

The utility of polarized protons for the investigation of new phenomena depends rather sensitively on the nature of the new physics. If a new charged vector boson were discovered in a hadron collider, it may prove very difficult to determine its couplings to quarks; for example, it is hard to distinguish V-A from V+A couplings with unpolarized beams. Polarized protons may prove to be an indispensable tool for unraveling the new physics, especially if the effects do not appear or are not readily accessible in ep or e^+e^- reactions.

In view of our ignorance of new physics, it would seem prudent to maintain a polarization option in future accelerators, to enable such devices to be adapted as easily as possible to the modifications of the lattice which polarized beams would require. Moreover, a demonstration of the capability for very high energy polarized protons should be encouraged, for example, by the design and construction of a model Siberian Snake.

Another, related topic which has been almost totally ignored in the past is the predictions of QCD for the evolution of the fragmentation of a polarized quark into a spinning hadron (most commonly a vector meson or baryon). It has been noted that the fragmentation functions also obey Altarelli-Parisi type equations[8], but the implications for helicity correlations have not been worked out, to the best of my knowledge. This could turn out to be even more useful than polarization in parton distributions, because quarks produced in parity-violating interactions typically have a preferential helicity, at least in certain directions. In addition, plans already exist to provide longitudinally polarized electrons at SLC and longitudinally polarized electrons and positrons at HERA. This in both unpolarized and polarized interactions, quark polarization can be anticipated. The issue is whether this information is transmitted to a spinning hadron in the quark jet. This subject is still under investigation and will be discussed elsewhere[9]. However, there appear to be some interesting results which suggest that this may be a useful tool for analysis. The fragmentation of charm and bottom quarks is known to be relatively "hard," i.e. there is a charmed meson or B-meson respectively in the jet carrying a substantial fraction of the jet momentum. The unmistakable interpretation is that the c (or b) quark winds up as a valence quark in a charmed (or B-) meson. (This is in contrast to lighter quarks where the abundance of pions and kaons in jets created as a result of the hadronization process

renders flavor-tagging impossible.) Quite frequently, the charmed meson in a c-quark jet is a vector D^* , so that one might expect a positive correlation between the valence quark helicity and the D^* helicity. In fact, there is a theorem similar to the one previously developed for non-singlet structure functions: If the polarization of a hadron in (nonsinglet) quark jet increases monotonically with z (the momentum fraction of the quark carried by the hadron), then the polarization of the hadron increases with energy (for fixed z). Like structure functions, the fragmentation functions evolve to smaller z as energy increases, but the helicity information of a quark is not lost if one observes a spinning hadron containing that quark as a valence quark. The correlation of the quark's helicity with the hadron's helicity has a constant average asymmetry. The singlet quark fragmentation function and gluon fragmentation function also transmit spin information. For example, the mean asymmetry of a singlet quark or gluon to fragment into a hadron of definite helicity grows as $\ln Q^2$. As with parton distributions, the asymmetry does not grow as rapidly as the multiplicity of hadrons, but this does not necessarily mean that one cannot extract interesting information from the helicity of the hadron.

If such helicity correlations in parton fragmentation are observable, they would expand enormously the kinds of measurements which could be performed and the detailed information which could be obtained about the Standard Model or new phenomena not encompassed by our present knowledge.

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